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REPETITIVE ELECTRON BEAM CONTROLLED SWITCHING

R. F. FERNSLER,* D. CONTE, I. M. VITKOVITSKY

Naval Research Laboratory
Washington, D.C. 20375

Abstract

Previous investigators have demonstrated the feasibility of using an ionizing electron beam to control the conductivity of a gaseous, volume-discharge switch. We have considered the possibility of using such switches repetitively at high power levels (up to 10^{10}W), with switch opening and closing times as short as several nanoseconds. An analysis of the relevent gas chemistry has indicated that these requirements can best be met by using a non-electronegative base gas diluted with a small percentage of an electronegative gas. Detailed chemistry simulations, using the non-electronegative gas N_2 and the electronegative gas O_2, have been performed and will be presented to support this analysis. Also discussed will be the limitations imposed by switch heating and gas breakdown.

Introduction

Hunter[1], O'Loughlin[2], and Kovalchuk and Mesyats[3] have described and demonstrated a switch concept which appears to be well suited to fast, high-power, repetitive switching. This concept consists (see Fig. 1) of a pair of planar electrodes separated by a high pressure gas. The switch is made to conduct by passing an ionizing electron beam through the gas, such that a volume discharge can be maintained between the switch electrodes. Such volume discharges have the property that once the electron beam is removed, the discharge rapidly extinguishes and the gas can again hold off the high voltage.

The use of high gas pressure allows for small electrode separation, thereby minimizing switch inductance. As a result, switch opening and closing are determined primarily by the electron beam and gas chemistry characteristics. The use of large electrode surfaces, on the other hand, allows large switch currents to be conducted before switch heating destroys proper switch behavior. The present paper seeks to assess the overall capabilities of these electron-beam controlled switches.

Gas Chemistry

The switch resistance is controlled by the electron density n_e of the gas medium. For a volume discharge whose dominant ionization source is an electron beam of current density J_b, n_e varies according to

$$\frac{d}{dt} n_e = J_b \frac{\sigma_i N}{e} - \alpha n_e - \beta n_e^2 - \gamma n_e^3 \qquad (1)$$

where σ_i is the cross-section for ionization by the electron beam, N is the gas density, α is the attachment rate, β is the two-body recombination coefficient, and γ is the three-body recombination coefficient. Eq. (1) must be supplemented by the circuit equation and by the switch current density equation

$$J_s = e\, n_e\, v_d(E/N) \qquad (2)$$

where v_d is the electron drift velocity due to the electric field E appearing across the switch.

Eqs. (1) and (2) dictate that the minimum switch closing time is given by

$$\tau_c(\min) = \frac{\overline{J_s}}{\overline{J_b}} \quad \frac{1}{\sigma_i N\, \overline{v}_d} \qquad (3)$$

where the bar denotes the steady-state value in the

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Previous investigators have demonstrated the feasibility of using an ionizing electron beam to control the conductivity of a gaseous, volume-discharge switch. We have considered the possibility of using such switches repetitively at high power levels (up to 10 10 W), with switch opening and closing times as short as several nanoseconds. An analysis of the relevent gas chemistry has indicated that these requirements can best be met by using a non-electronegative base gas diluted with a small percentage of an electronegative gas. Detailed chemistry simulations, using the non-electronegative gas N2 and the electronegative gas o2, have been performed and will be presented to support this analysis. Also discussed will be the limitations imposed by switch heating and gas breakdown.

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closed (conducting) circuit state. Eqs. (1) and (2) similarly determine the minimum switch opening time, which is defined as the time for n_e to decay from $\bar{n}_e$ to 0.1 $\bar{n}_e$. For a switch dominated by electron attachment, the minimum opening time is

$$\tau_a = 2.3\ \tau_c^{(min)}; \tag{4a}$$

for a switch dominated by two-body recombination, it is

$$\tau_2 = 10\ \tau_c^{(min)}; \tag{4b}$$

and for a switch dominated by three-body recombination, it is

$$\tau_3 = 50\ \tau_c^{(min)}. \tag{4c}$$

These latter three equations demonstrate that attachment-dominated switches minimize the switch opening time, without seriously compromising the switch closing time. (A second advantage is flexibility, in that the attachment rate α can be readily varied by using a non-attaching base gas diluted with controlled percentages of an attaching gas.)

To insure that the gas is everywhere ionized, the beam electrons must have sufficient energy to traverse the entire discharge. Simple analysis shows that this energy constraint leads to

$$\tau_c^{(min)} \geqslant Q\ \frac{\epsilon_i}{eE_o\ \bar{v}_d} \tag{5}$$

where the switch efficiency Q is the ratio of the power dissipated in the load to that consumed by the electron beam generator, where ϵ_i is the average energy required per beam ionization in the gas, and where E_o is the open-circuit field strength originally appearing across the switch. This equation demonstrates that a trade-off exists between high efficiency Q, and short opening and closing times $\tau_c^{(min)}$.

Switching characteristics of 10 atm of N_2 with small admixtures of O_2 have been calculated using a detailed air chemistry code.[4] These sample calculations were designed to assess the performance of a switch soon to be constructed and tested at the Naval Research Laboratory. The switch nominally imposes 200 kV across a 20 Ω load. The switch electrodes are 1000 cm^2 in area and are separated by 2 cm. Nominal switch efficiency is $Q \sim 10$. The calculations assume that the electron beam current rises instantaneously to full value (1 kA) at time zero, and instantaneously decays to zero at 100 nsec. The predicted behavior, shown in Fig. 2, demonstrates that the O_2 concentration significantly affects the switch opening time, without significantly affecting the switch closing time.

Multipulse Operation and Other Considerations

Volumetric switches minimize the volumetric heating rate such that the gas temperature and physical state of the gas are largely unaltered by a short, single switching pulse. This factor accounts for the rapid recovery and short opening times of volume discharges as compared with the behavior of filamentary arc discharges.[5]

Conversely, volumetric switches cannot be cooled rapidly, and hence gas heating may eventually pose problems for switches that are repetitively pulsed. These problems take three forms.

The first relates to cumulative changes in the chemical and electrical properties of the gas. Studies of discharges in N_2 suggest that such alterations are unimportant until sufficient energy has been deposited to raise the gas temperature to above 2000° K.[5]

The second problem is a structural one related to excessive pressures generated by the heated gas. This problem is severely compounded by the use of a thin foil window (see Fig. 1) required to pass the electron beam into the discharge volume.

The third problem concerns reductions in the gas density N produced by the elevated gas pressure. The main problem here stems from the constraints imposed on the ratio E_o/N, where E_o is the open-circuit field strength. To justify ignoring cascade

ionization of the gas by the gas conduction electrons, E_o/N must typically satisfy[6]

$$E_o/N \leq 10^{-16} \text{ volts - cm}^2. \qquad (6)$$

At the same time, Eq. (5) demonstrates that E_o must be maximized to obtain high efficiency Q and short closing times $\tau_c^{(min)}$. Hence, reductions in N, due to elevated gas pressures, reduce the allowed field strength E_o, thereby degrading Q and/or $\tau_c^{(min)}$.

The preceding discussions suggest that a conservatively operated switch is one for which the total energy deposited within the switch from a given pulse train is less than, say, the total kinetic energy originally contained in the gas. This prescription insures that alterations in the gas temperature, pressure, and density will be less than a factor of 2.

The total energy deposited in the switch, from the electron beam and from Joule dissipation, can be related to the total energy absorbed by the load via a net efficiency factor Q', where Q' ≤ Q. For a pulse train consisting of m pulses, each of conduction time τ_p, we thus require that

$$(m\, \tau_p\, \overline{J}_s\, E_o) \;/\; Q' < \frac{3}{2} Nk\, T_o \qquad (7)$$

where k is Boltzmann's constant and T_o is the initial gas temperature. The breakdown constraint (6) thus suggests that, for $T_o = 300^o$ K, gas heating effects can generally be ignored provided

$$m\, \tau_p\, \overline{J}_s \leq 10^{-5}\, Q' \text{ A - sec/cm}^2 \qquad (8)$$

Several other limitations apply to electron beam controlled switches. An important one is the inherent switch inductance, which is minimally given in nH by the electrode separation distance in cm. Using constraint (6), this inductance can be shown to limit the switch opening and closing times to

$$\tau(\text{sec}) \geq 10^7 \; \frac{\overline{I}_s\ (A)}{N(cm^{-3})} \qquad (9)$$

where $\overline{I}_s$ is the desired switch current. This result reiterates that optimum performance is attained by maximizing the gas density N. It is interesting to note that constraint (9), coupled to Eq. (3), limits the maximum practical electron beam current to a value typically given by

$$I_b \leq 10^4 \text{ A}; \qquad (10)$$

i.e., raising I_b above this inductive limit only degrades switch performance by reducing efficiency Q without reducing opening or closing times τ.

Summary

The preceding sections have outlined the general features of electron beam controlled switches. These devices may be viewed as current amplifiers in which a small beam current regulates a large discharge current. They may be operated either in a fast, high-power mode or in a slow, high-energy transfer mode. In the former case, the present analysis indicates that, at 10 atm gas pressure, current switching rates can approach 10^{13} A/sec; these rates correspond to switch closing times of several nsec and switch opening times of tens of nsec, for switch efficiencies Q, Q' ∿ 10. Total energy transfer would be roughly limited, however, to 10 Joules per cubic centimer of discharge volume. Higher energy transfer can be obtained by degrading switch response time, or by raising the gas pressure.

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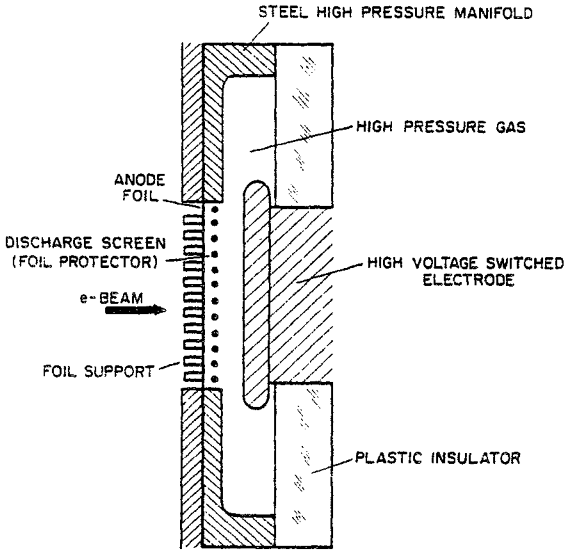

Fig. 1. Cross-sectional schematic of an electron beam controlled switch.

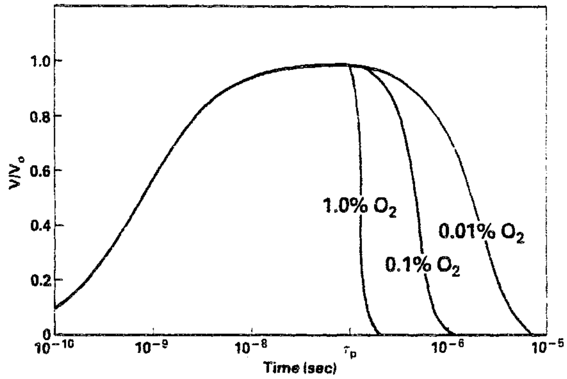

Fig. 2. Typical characteristics of an electron beam controlled switch operating in 10 atm N_2 with different O_2 admixtures. V is the voltage across a 20 Ω resistive load, while V_o (200 kV) is the source voltage. A 150 keV, 1 kA electron beam is passed through the discharge volume of 2 cm by 1000 cm^2 for a time τ_p = 100 nsec.